

Super star clusters and Supernovae in interacting LIRGs unmasked by NIR adaptive optics

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Abstract We report on an on-going near-IR adaptive optics survey targeting interacting luminous IR galaxies. High-spatial resolution NIR data are crucial to enable interpretation of kinematic, dynamical and star formation (SF) properties of these very dusty objects. Whole progenitor nuclei in the interactions can be missed if only optical HST imaging is used. Here we specifically present the latest results regarding core-collapse supernovae found within the highly extinguished nuclear regions of these galaxies. Direct detection and study of such highly obscured CCSNe is crucial for revising the optically-derived SN rates used for providing an independent measurement of the SF history of the Universe. We also present thus-far the first NIR luminosity functions of super star cluster (SSC) candidates. The LFs can then be used to constrain the formation and evolution of SSCs via constraints based on initial mass functions and cluster disruption models.

1 Introduction

Interacting and merging galaxies are sites of violent star formation (SF) in extreme environments, as well as sites of the most massive known clustered star formation. Many of these objects are classified as luminous or ultra-luminous IR galaxies (LIRGs have $\log(L_{IR}/L_{\odot}) = 11 - 12$ and ULIRGs $\log(L_{IR}/L_{\odot}) > 12$). Though it is still debated exactly how much of the high-redshift SF is interaction triggered, and how local ULIRGs relate to their higher- z cousins, it nevertheless is clear that a significant fraction, if not most, of SF in the high- z universe is happening in these extreme environments. It is thus important to understand the physical processes in

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local examples, where detailed studies are possible, over a wide range of L_{IR} and SF-rate (SFR) output, and a range in environment and interaction stage.

Moreover, much of the most violent SF is hidden behind dust. The total SF output can be estimated from far-IR luminosities, but the spatial resolution is usually too low to see more details of e.g. the spatial distribution of SF. We have used NIR adaptive optics (AO) to image a sample of < 200 Mpc LIRGs to bridge the gap between high-resolution optical imaging and the mid/far-IR (U)LIRG studies. See [12, 20, 22] for more information of the observations and data. We have looked for the elusive population of core-collapse SNe and for populations of massive super star clusters (SSCs), in addition to studying the galaxies themselves.

2 Super star cluster candidates

Most stars are born in clusters but most stars within galaxies do not live in clusters. This basic observation has led to a lively discussion on the physical processes involved in SSC formation and evolution, their disruption and survival, and how they can be used to trace SF and dynamical histories of their host galaxies. SSCs with masses even up to $10^7 M_{\odot}$ have been found in large numbers especially in interacting galaxies (e.g. [2] for a recent review). However, it still remains unclear whether the most massive clusters can only form in starburst environments, or are SSCs seen in those locations just because of larger number statistics. SSC studies have thus far been driven by optical HST observations, and we now add the first significant NIR sample to be studied further. We detect from a dozen to hundreds of SSC candidates per galaxy in our sample of LIRGs (Fig. 1).

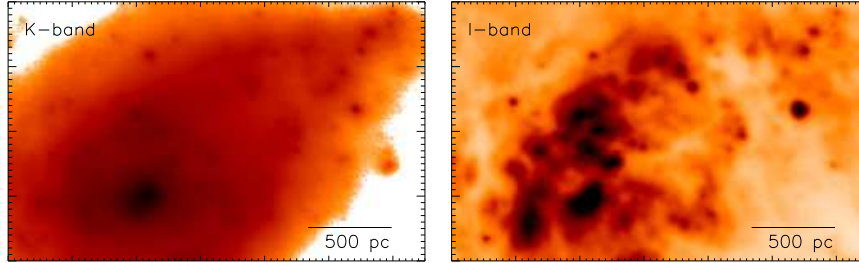


Fig. 1 A region of $6'' \times 4.5''$ North-West of the nucleus (at bottom left) of IRAS 18293-3413 showing dozens of SSC candidates. Our VLT/NACO data is on the left and HST/ACS I-data on the right: SSCs are only partially detected simultaneously in the two wavelengths because of a combination of extinction and age effects.

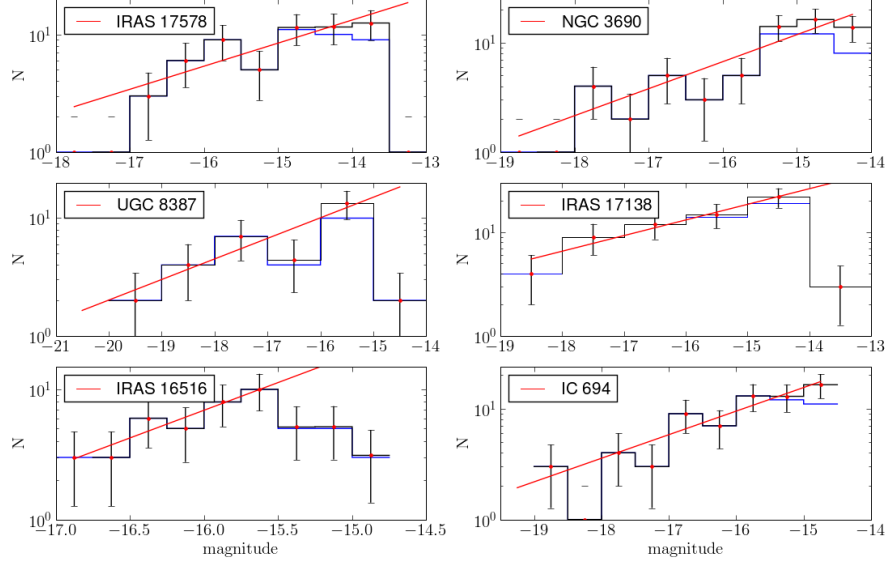


Fig. 2 A preliminary K-band LF of SC candidates in our sample of Gemini images. The black histogram and red data points show completeness corrected SSC number counts against K-band absolute magnitude, and the straight red lines the weighted least-squares fit. The blue histogram is the raw SSC count. Intriguingly, the power law LF index in these cases shows quite consistently $\alpha \sim -1.6$, significantly shallower than those seen in the optical.

2.1 The SSC NIR luminosity function

The current debate over basic SSC system characteristics involves questions such as: are the mass and luminosity functions (LF/MF) of SSCs universal, or galaxy or mass dependent, are the MFs/LFs described with power-laws, Schechter functions or Gaussians, and is SSC disruption internally driven and mass-independent or mass dependent and externally driven (see e.g. [9, 5, 4, 3] and references therein). There clearly is need for more data, preferably of new and varied targets and at different wavelengths.

While waiting to complete our Gemini survey, we have already started putting together epoch-stacked deep images to study the LIRGs themselves. As a preliminary result, Fig. 2 shows the first ever K-band luminosity function of SSCs in external galaxies from six of our targets (Randriamanakoto et al., in prep.). The LF slope alone is a useful diagnostic to probe SC formation/evolution since different disruption models result in different LFs and would indicate different initial LFs and MFs (e.g. [6]). Intriguingly, the fitted LF slopes are fairly consistently around $\alpha \sim -1.6$, i.e. significantly shallower than in optical studies which typically find values of $\alpha \sim -2$. At face value, this would indicate support for models advocating non-universal, mass-dependent, LFs; in case of a universal power law index of

$\alpha \sim -2$ with mass-independent disruption, even though the observed LF is a sum of SSCs of different ages and masses, the final LF should show the same $\alpha \sim -2$ slope.

Detecting SSCs in the K-band might be expected to result in different slopes given both extinction and age effects, however – in the NIR we are seeing, at least partially, a more obscured population, and also likely a somewhat older population compared to the optically detected SSCs. The age difference might not necessarily be widely different, however: our Starburst99 modelling indicates that the K-band is likely to pick out SSCs close to age ~ 10 Myr, while the optical SSCs peak only slightly earlier (excluding extinction). Nevertheless, more careful analysis of completeness and selection effects are needed to securely reach implications from our preliminary SSC NIR-LF results presented here.

3 Searching for extincted core-collapse SNe

SF dominated (U)LIRGs are expected to hide in their central regions large numbers of undetected core-collapse supernovae (CCSNe), i.e. stars more massive than $\sim 8 M_{\odot}$ exploding at the end of their (short) lives. LIRGs with SFRs of tens to hundreds of M_{\odot}/yr can be expected to host $\sim 0.2 - 1$ CCSNe/yr, a couple of orders of magnitude higher rate than in ordinary field galaxies. Radio observations have revealed hidden SN factories in the nuclear regions of (U)LIRGs, e.g. [19, 16]. Such SNe cannot be detected at optical wavelengths, even in the local universe, because of severe ($A_V > 10$ mag) dust extinction. However, they *must* exist in the nuclear (central kpc) regions of such galaxies, if the high SFRs derived from their IR luminosities and spectra are to be believed.

Previous NIR searches [10] have found an SN-rate lower by factors of several than expected. We have argued [11] that this rate misses the SNe exploding close to the centres of LIRGs in very extinguished regions, and have an on-going program to search for these cases making use of AO-assisted NIR imaging.

SN2004ip was detected in a pilot study using VLT/NACO [12]. It was at a projected distance of $1.4''$, or 500 pc, from the nucleus of IRAS 18293-3413, among the closest SNe detected (in IR) to a LIRG nucleus. Our subsequent radio observations confirmed its CCSN nature [15]. Our current Gemini/ALTAIR/NIRI search has so far produced 3 new SNe. The first one was SN2008cs [7], located at $4.2''$, or 1.5 kpc, projected distance from the nucleus of IRAS 17138-1017. Follow-up observations in both radio and NIR bands were again consistent with a core-collapse event, and showed the SN to suffer from a very high host galaxy extinction of $A_V \approx 16$ mag, the highest definite measurement yet for any SN. In addition, a “historical” SN2004iq was detected in the same galaxy from HST images, and is located 660 pc from the nucleus. Earlier this year, three more SNe were detected in our Gemini programme, though two of them were actually first seen in non-AO optical and NIR searches [14, 13, 17] thanks to their relatively large galactocentric distances. The third one

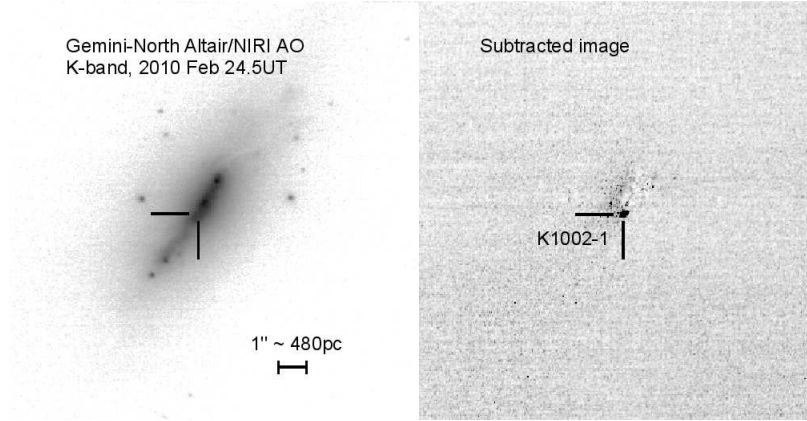


Fig. 3 The central regions of IC 883 observed with Gemini. The location of the recent SN candidate PSN K1002-1 is marked, though it is visible only in the subtracted image from two different epochs in the right panel. The projected distance to the core of the galaxy is a mere 180 pc.

[8] in IC 883, however, turned out to be the closest SN to a LIRG nucleus yet discovered, at just 180 pc (or 0.4'') projected distance from the core (Fig. 3).

The intrinsic number of CCSNe based on the FIR-luminosities for our sample of 7 galaxies over the Gemini program is calculated to be about 10 SNe. Though the number statistics are arguably still low, and though we have not finished the survey, with 5 SN detections in the sample it already appears clear that AO-assisted NIR observations provide an excellent window to detect SNe in the obscured nuclear regions of nearby LIRGs.

4 SF and dynamics in interacting galaxies

We have followed-up in detail two of our early high-quality deep NACO AO images. In addition to combining the AO-data with archive optical HST imaging we obtained spectroscopy using SALT and AAT. Both cases revealed surprises. We found an unexpected third component in the supposed pair-interaction of IRAS 19115-2124, dubbed the Bird [20]. Moreover, this third, least massive and irregular component dominates the current star-formation output of the whole system. This is in contrast to the widely held picture that tidal interactions are expected to drive large quantities of gas into the *central regions* of the interaction resulting in starbursts. While there is strong SF in the central regions as well, it clearly is the smaller “extra” component that elevates the Bird into almost a ULIRG-class object. We are in the process of studying this system further with integral field spectroscopy and mid-IR imaging to piece together what has happened in this intriguing system.

Follow-up of IRAS18293-3134, on the other hand, showed evidence of an extremely rare leading-arm spiral, i.e. a galaxy where the spiral arms open up in the

same direction as the disk is rotating [21]. Simulations have shown that some retrograde encounters should produce these kind of galaxies [18], though they have not been studied much and only a couple of candidates exist in the literature [1]. Their very existence, however, would have implications for e.g. the dark matter halo mass of spirals.

Both of these systems highlight the fact that NIR-AO imaging is crucial in interpreting the dynamical state of dusty LIRGs. Relying only on optical data, even HST-data in the I-band, will often not reveal all the components of the interactions and will not resolve the locations of major stellar mass distribution. Without the NIR AO-data it would have been virtually impossible to disentangle the true velocity dispersions of the nuclei from other kinematic components such as tidal tails and gas outflows. Similarly, the leading arms of IRAS 18293-3134 would not have been possible to detect without NIR AO-data, raising the tantalizing possibility that more such cases might be hidden in the chaotic interactions of dusty LIRGs.

5 Summary

We have presented results of our on-going survey to unmask CCSNe in the highly extinguished nuclear regions of interacting luminous IR galaxies, and presented, for the first time, luminosity functions of SSCs found in these galaxies in the NIR.

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